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## A search for high redshift clusters associated with radio galaxies at $2 < z < 4$

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**Abstract.** High redshift radio galaxies are amongst the most massive galaxies in the early Universe and have properties expected from central galaxies in forming clusters. We are carrying out an observational programme on the VLT to find and study galaxy proto clusters around radio galaxies at redshifts  $2 < z < 4$ . First, we use narrow band imaging to select candidate galaxies which show excess Ly $\alpha$  emission at redshifts similar to the central radio galaxy. Then, we use multi object spectroscopy to confirm the redshifts of these candidates and measure the velocity dispersion of the cluster members. Our goal is to observe a sample of  $\sim 10$  targets and investigate galaxy overdensities as a function of redshift. Here, we report on the current progress of the programme and show some preliminary results which include the discovery of a structure of galaxies at redshift 4.1.

### 1. Introduction

Searching for clusters of galaxies or their progenitors (proto clusters) at redshifts  $> 2$  is important for constraining galaxy evolution, large scale structure formation and cosmological models (e.g. Giavalisco et al. 1998, Bahcall, Fan, & Cen 1997). Radio galaxies can act as beacons of these distant structures.

Luminous radio galaxies are the oldest and most massive known galaxies in the early Universe (De Breuck et al. 2000). In standard cosmological models massive galaxies form in the deepest of the first potential wells, in which - at either a later or earlier time depending on the galaxy formation model - other galaxies will form to assemble a cluster. There exists a diverse collection of evidence that high redshift radio galaxies (HzRGs) are actually residing in dense cluster environments, which includes: (i) the excess of companion galaxies around HzRGs (e.g. Röttgering et al. 1996), (ii) the extreme radio rotation measures of HzRGs indicating that they are embedded in hot magnetized gas (Carilli et al. 1997), and (iii) giant Ly $\alpha$  emitting gas halos surrounding HzRGs which can extent up to 200 kpc (e.g. Kurk et al. 2001).

In principle, using narrow band imaging in rest-frame Ly $\alpha$  star forming galaxies can be found effectively over a narrow redshift range. However, since

there is only a small amount of dust needed to extinguish Ly $\alpha$  emission from recombining hydrogen ions, it was not clear whether Ly $\alpha$  photons could escape at all from star forming galaxies (Pritchett 1994). Now, using large telescopes several searches for Ly $\alpha$  emitters are underway and show good results (Rhoads et al. 2000, Stiavelli et al. 2001). With the presumption that powerful radio galaxies are located in overdense regions, we have started a search for high redshift clusters using the narrow band imaging technique to target Ly $\alpha$  emitting galaxies around radio galaxies at redshifts  $2 < z < 4$ .

## 2. The sample

From our collection of almost 150 radio galaxies at  $z > 2$ , we have chosen eight objects with redshifts suitable for Ly $\alpha$  imaging with the available narrow band VLT/FORS filters: four at  $z \sim 2$  and three at  $z \sim 3$ , while for two more galaxies at  $z = 4.1$  a custom filter was manufactured. These galaxies were also selected on their large radio, optical/IR continuum and Ly $\alpha$  luminosities, which are characteristics of massive galaxies. For each of the ten radio galaxy fields we (plan to) do spectroscopy of  $\sim 40$  emitter candidates and aim to confirm  $> 15$  emitters. With this sample, we can study what fraction of HzRGs are located in galaxy overdensities and how properties of these overdensities (e.g. velocity dispersions, sizes) and its cluster-galaxies (e.g. rotation curves, star formation rates) change with redshift. Simultaneously, we can study the giant gas halos associated with the radio galaxies.

Currently, imaging of five fields has been carried out, resulting in the detection of fifteen to sixty emitters in each field with Ly $\alpha$  rest frame equivalent width  $> 20$  Å and significant signal-to-noise. Multi object spectroscopy has been completed for two fields: MRC 1138-262 and TN J1338-1942. The latter has the largest redshift of our sample and is described in the following section. The former was the subject of our pilot project and is described in detail by Pentericci et al. (this volume). Briefly, the existence of 14 Ly $\alpha$  emitters in this field was confirmed, with redshifts close to the radio galaxy but distributed in two groups (grey histogram in Fig. 1).

## 3. TN J1338-1942 at $z = 4.1$

About 25 candidates with above mentioned selection criteria were discovered in the field around TN J1338-1942. Subsequent spectroscopy of 22 of these led to the confirmation of 20 Ly $\alpha$  emitters at  $z \sim 4.1$  (Fig. 2). Their spatial distribution is inhomogeneous: it is extended in the direction of the radio axis and Ly $\alpha$  halo of the radio galaxy (Fig. 2). Their velocity distribution (black histogram in Fig. 1) is narrower than that of MRC 1138-262 and has a dispersion ( $\sigma_v$ ) of  $\sim 350$  km s $^{-1}$  which implies a total virial mass ( $M_{\text{vir}}$ ) of  $2 \times 10^{14}$  M $_{\odot}$ , assuming spherical symmetry with a virial radius ( $R$ ) of 1.5 Mpc, using  $M_{\text{vir}} = 5 R \sigma_v^2 / G$ , where  $G$  is the gravitation constant. To determine whether we actually observe an overdensity here with respect to a field which does not contain a (proto) cluster, we have compared the number density of emitters around 1338-1942 with observations of blank fields by Cowie & Hu (1998) and Rhoads et al. (2000). The number density of emitters around 1338-1942 is five

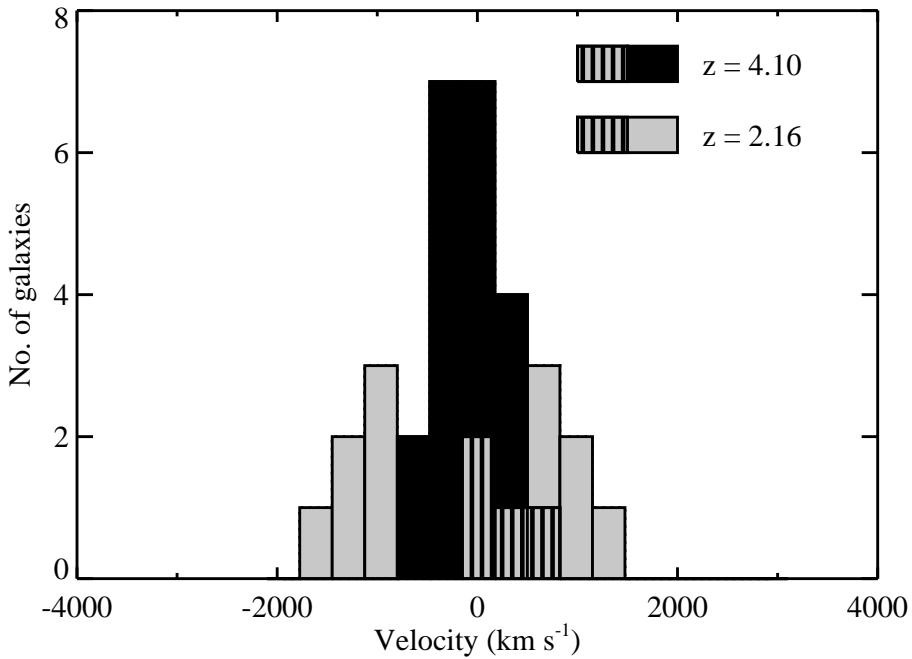


Figure 1. Velocity distributions of confirmed emitters around MRC 1138-262 at  $z = 2.16$  (grey histogram) and TN J1338-1942 at  $z = 4.11$  (black histogram). The emitters around 1138 are clustered in two groups, separated by  $\sim 1800 \text{ km s}^{-1}$ , while the emitters around 1338 have approximately a Gaussian distribution around the radio galaxy.

times higher than the field density and comparable to the density of emitters around 1138-262.

#### 4. Conclusions and outlook

Using narrow band imaging and subsequent multi object spectroscopy on the VLT, we have confirmed the existence of concentrations of galaxies around radio galaxies at  $z = 2.2$  and  $4.1$ . These observations are consistent with the idea that HzRGs are brightest cluster galaxies in forming clusters. Furthermore, it shows that narrow band imaging at the wavelength of redshifted Ly $\alpha$  is an effective method to find (proto) clusters at high redshift. We expect to uncover several more of these structures in the coming years. Obviously, these systems will be subject to further study at a multitude of wavelength bands, contributing important clues to outstanding questions in galaxy formation and cosmology.

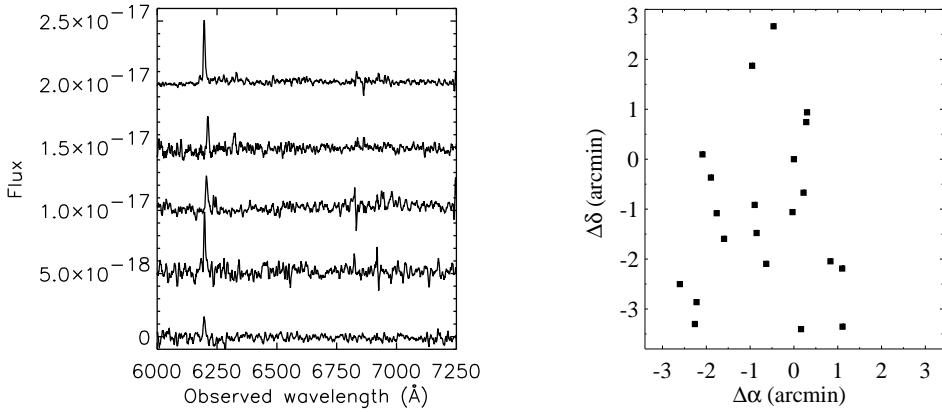


Figure 2. *Left* Spectra of five Ly $\alpha$  emitters found in the field of TN J1338-1942. *Right* Positions of the Ly $\alpha$  emitters around the radio galaxy TN J1338-1942. The radio galaxy itself is located at the origin.

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